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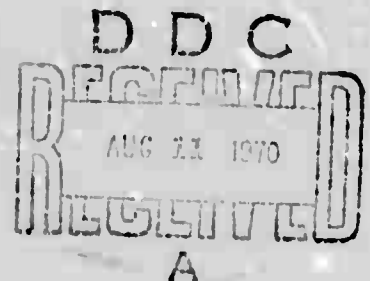
Development of High Performance Composites

CONTROLLING FLOW ORIENTATION IN MOLDING
OF SHORT-FIBER COMPOUNDS

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Controlling flow orientation in molding of short-fiber compounds

The degree of fiber orientation produced in transfer or plunger molding of short fiber-filled epoxy molding compounds, and hence their mechanical properties, can be controlled by mold design, processing conditions, and formulation, as well as by part design. A quantitative relationship is found to exist between three-dimensional orientation distributions and tensile modulus of the moldings.

An engineering feature

Jack E. Hauck, engineering editor

Some qualitative principles relating the orientation of suspended rods to hydrodynamic conditions can be applied to the flow of fiber-filled molding compounds. The enlarging cross-section that a fiber-filled melt flow experiences as it emerges from a small gate into a large mold cavity causes a deceleration. Resulting hydrodynamic forces orient the fibers at the center of the molding in the transverse direction. Shear and other flow effects cause longitudinal fiber alignment near the wall of the cavity. Thus the molded structure has a transversely oriented core which is surrounded by a longitudinally oriented skin (Fig. 1).

The high degree of alignment of fibers in the direction of flow in the mold's runner results from the converging flow that occurs in the melt's passage from the pot to the runner. The acceleration caused by a reduction in cross-

section at this point stretches the fluid and aligns the fibers.

In an oblong piece (a simple $1/4 \times 6$ in. bar was used to simplify interpretation of data), it is usually advantageous to have the greatest strength and stiffness in the direction of the length of the bar. This would be achieved by aligning the fibers into a longitudinal orientation: all fibers parallel to the sides of the bar and in the direction of flow. Transversely oriented fibers contribute very little, if anything, to strength and rigidity.

Orientation controlled by processing

By properly selecting the flow characteristics of the molding compound, the molding conditions, and the type of gating, the orientation distribution in the molding can be controlled. Some changes can be made with a minimum of retooling and compound costs:

1) *Gate design.* Orientation produced by fan gates depends strongly upon the fill rate and may be considerably more transverse than that produced by edge gates (Fig. 2). Among edge gates (Fig. 3), the largest (e.g., 0.019 in. or 0.060 by $1/4$ in.) produce a somewhat larger component of orientation in the longitudinal direction.

Table I: Properties of epoxy compounds

Compound	Epoxy groups unreacted, %	Resin viscosity at 260° F. and low shear, poise	Spiral flow length, in.
A*	38-44	10,000	8
B*	57-63	500	12

a— $1/8$ -in. fiber length, 40% (vol.) fiber content.

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Table II: Angle distributions and mechanical properties of fiber-filled moldings

Compound	Gate type	Bar size, in.	Fill rate cu. in./min.	Temp., °F.	Angle about flow direction for 75% of fibers, deg.	Tensile strength, p.s.i.	Tensile modulus p.s.i. $\times 10^{-4}$
A	Fan	$1/4 \times 1$	4.4	260	77-84	4,200	1.7
A						(2,800 ^a)	(0.9 ^a)
	Edge	$1/4 \times 1$	7.5	260	63-76	5,500 ^a	1.4 ^a
B	Fan	$1/4 \times 1$	1.1	260	40-50	7,600	2.3
B	Edge	$1/4 \times 1/2$	2.8	260	25-50	15,000	2.7

a—Water present.

This orientation is about equal to the highest level obtained with the fan gates.

2) *Fill rate.* With edge gates equal to or smaller than $\frac{1}{4}$ by 0.060 in., there is no effect of fill rate on the orientation in the molded bar. However, that is not the case for the fan gates. The highest degree of longitudinal orientation is produced by a very large fan gate at a low fill rate or by a very small gate at a high rate. This flow rate dependence suggests two mechanisms by which the orientation becomes more longitudinal. First, there is the squirting effect which occurs during fast fills through a small gate. Second, at slow fills through a very large gate, the longitudinal orientation from the runner can be kept intact through the gate to produce a large, longitudinally aligned envelope or skin at the walls of the bar (Fig. 4).

3) *Viscosity of the matrix.* Low-viscosity compounds (Table I) produce higher degrees of longitudinal orientation than do compounds that typically have only 38 to 44% unreacted epoxides. (A measure of the relative viscosities of B-staged epoxy molding compounds made from the same components is the fraction of available



Fig. 1: Orientation patterns (dark streaks) of glass fibers in runner, gate, and mold cavity.

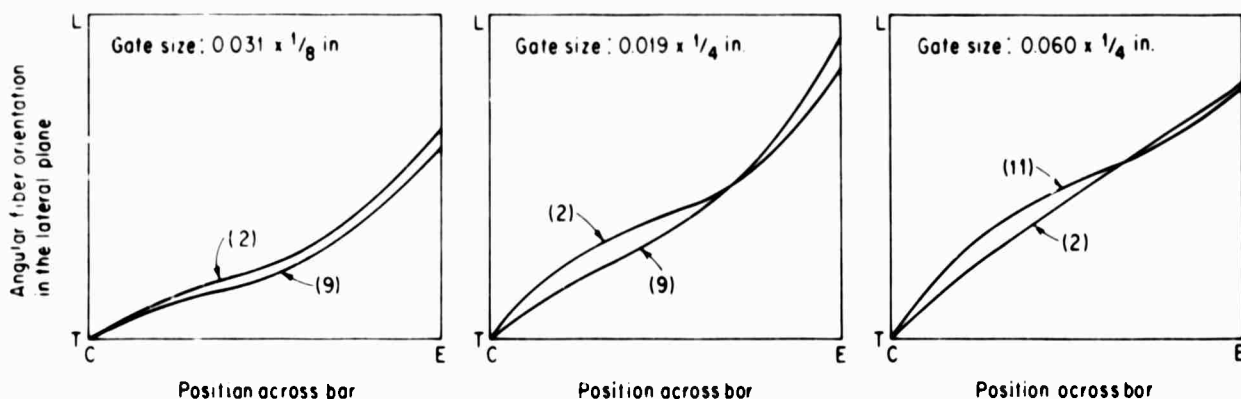


Fig. 2: Fiber orientation in molded bar (Compound A, $\frac{1}{4} \times 1 \times 6$ in.) produced by a 1-in.-wide fan gate at end of the bar. L = longitudinal; T = transverse; C = center; E = edge. Numbers in parentheses designate flow rate, cu. in./min.

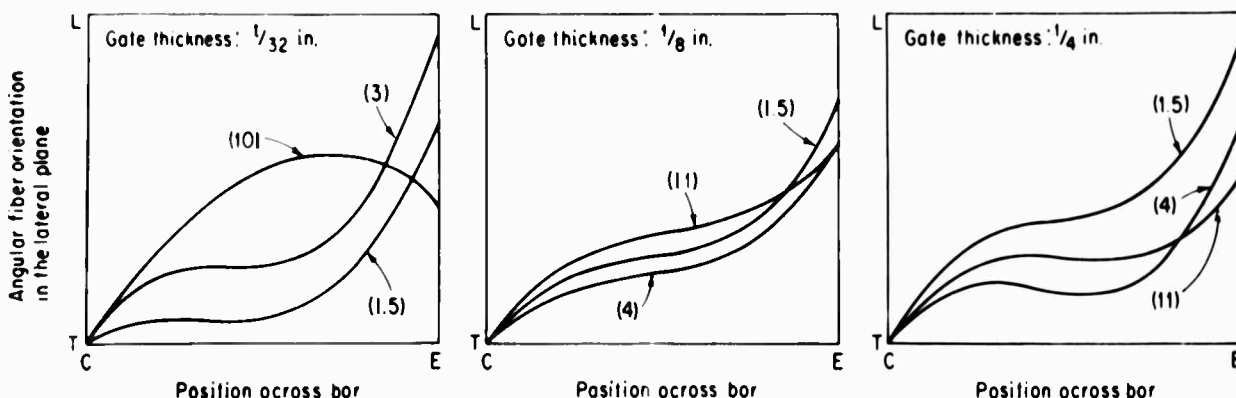


Fig. 3: Fiber orientation in molded bar ($\frac{1}{4} \times 1 \times 6$ in.) produced by a 1-in. edge gate at end of the bar (Compound A).



Fig. 4: Effect of fill rate on glass fiber orientation (dark areas) using large fan gate (Compound B). Fill rate, cu. in./min., was as follows: A, 5.3; B, 1.8; C, 1.1.

epoxide units that remain unreacted.) The high degree of longitudinal orientation obtained with the low-viscosity compounds is particularly evident with slow fills through the larger fan gates and for the high fill rates through the edge gates.

But in molding at a moderate fill rate of 5 cu. in./min. through the large fan gate, compounds that contained 44 and 57% epoxide groups unreacted and a commercial epoxy molding compound containing 45% (volume %) of $\frac{1}{4}$ -in.-long glass fibers were found to produce a similar, practically transverse, orientation distribution.

Lower viscosity, naturally, also can be obtained by increasing the mold temperature. For fill rates exceeding 5 cu. in./min. through the large fan gate, the longitudinal skin is thicker at the higher temperatures (Fig. 5).

4) *Mold lubrication.* Mold release agents have a negligible effect on the orientation pattern. A heavy application of silicone mold release caused the over-all fiber direction to be 2 to 3 deg. further away from the longitudinal position than when no lubrication was used. The film of mold release absorbs some of the shearing action that contributes to longitudinal orientation.

Part geometry exerts most effect

Although the processing conditions have an influence on the various orientation distributions, only limited changes are possible. For example, the longitudinal skin could be made larger, but a transversely oriented core still persists. Orientation can be controlled best by integrating converging and diverging sections into the design of the molding and selectively placing the gating to produce the desired flows.

Converging flow patterns result in a high degree of alignment in the direction of flow starting at the point of cross-section change (Fig. 6). Angle measurements show that practically all fibers in the plane lie within 15° of perfect longitudinal alignment.

The three-dimensional orientation distribution for this case is related to some mechanical properties in the last entry of Table II. The table is arranged so that the degree of longitudinal orientation increases down the listing. The first entry corresponds to the lowest orientation curve depicted in Fig. 2. When the bar thickness decreases to $\frac{1}{8}$ in. in the second entry, the orientation becomes more longitudinal because the shear stresses are larger and the diverging flow or expansion at the gate is less severe. Entry 3 corresponds to the photograph in Fig. 4C, where the size of the longitudinal skin is increased by decreasing the fill rate.

Maximum properties and the highest degree of longitudinal alignment are obtained for the converging flow caused by a reduction in cross section. But this alignment is still not optimum, as very few fibers are actually aligned within 25° of the flow axis. It should be possible to improve the alignment by changing flow conditions in this type of flow to produce strengths of 30,000 p.s.i. and tensile moduli of 5×10^6 p.s.i. For the same orientation distribution, strengths higher than those reported here could probably be obtained by using a less brittle matrix.

A quantitative relationship exists between the three-

dimensional orientation distributions in bars made under various conditions and their measured tensile modulus. Through mathematical techniques described elsewhere¹, the measured orientation is characterized in terms of an average angle about the flow axis (longitudinal direction).

1. E. A. Goettler, "Flow orientation of short fibers in transfer molding," 25th Anniversary Meeting, Reinforced Plastics/Composites Div., SPI, Washington, D.C., Feb. 1970.
2. J. C. Halpin, "Stiffness and expansion estimates for oriented short fiber composites," *J. Comp. Materials* 3, 732 (1969).

This orientation is plotted against the modulus in Fig. 7. The limiting values at the ends of the curve are predicted by equations developed by Halpin and Tsai for composites containing well-aligned discontinuous fibers¹. Most of the data were observed to lie on the expected interpolation between these limits. However, some highly transverse samples did show an abnormally low modulus. This probably results from a lack of bonding between fibers and the resin in some transverse planes.—END

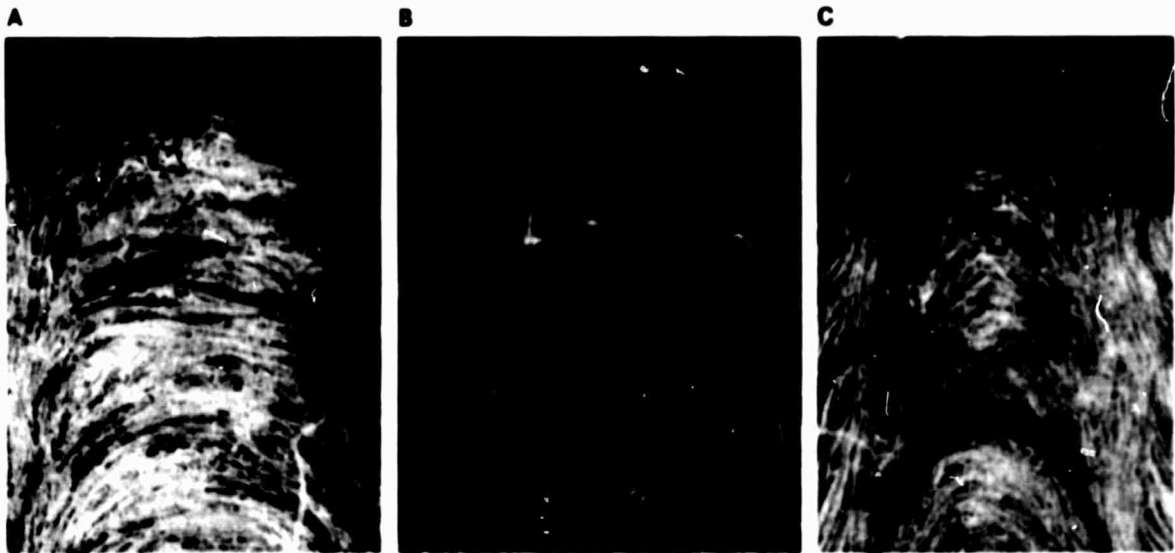


Fig. 5: Effect of mold temperature on glass fiber orientation (dark areas) using a large fan gate (Compound B). Temperature, °F., was as follows: A, 200; B, 260; C, 300.



Fig. 6: Converging section in part design results in longitudinal fiber orientation. Flow direction is upward.

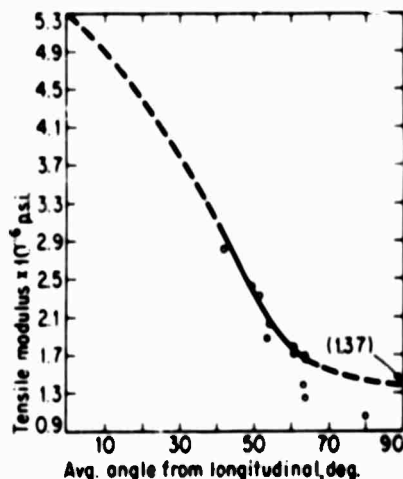


Fig. 7: Young's modulus versus longitudinal fiber orientation for 50% volume, 1/8-in. glass fiber in epoxy. Dashed line is extrapolation to limits predicted by Tsai-Halpin equations (see footnote 2 above).